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# Life Cycle Inventory
# of Biodiesel
# and
# Petroleum Diesel
# for Use in an Urban Bus


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# Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus

## *Final Report*

May 1998

by

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Prepared for:

U.S. Department of Energy's
Office of Fuels Development

and

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# Executive Summary

## What is biodiesel?

Biodiesel is a renewable diesel fuel substitute. It can be made from a variety of natural oils and fats. Biodiesel is made by chemically combining any natural oil or fat with an alcohol such as methanol or ethanol. Methanol has been the most commonly used alcohol in the commercial production of biodiesel. In Europe, biodiesel is widely available in both its neat form (100% biodiesel, also known as B100) and in blends with petroleum diesel. European biodiesel is made predominantly from rapeseed oil (a cousin of canola oil). In the United States, initial interest in producing and using biodiesel has focused on the use of soybean oil as the primary feedstock mainly because the United States is the largest producer of soybean oil in the world.

## Why biodiesel?

Proponents of biodiesel as a substitute for diesel fuel (in blends or in its neat form) can point to a number of potential advantages for biodiesel that could support a number of strategies for addressing national issues.

- ✓ ***Reducing dependence on foreign petroleum…***
  Petroleum imports are at record levels in the United States, and will continue to rise as domestic supplies of oil shrink. Our transportation sector relies almost exclusively on petroleum as a source of energy. This is due to the high level of demand for gasoline and diesel fuel. Biodiesel can be produced domestically from agricultural oils and from waste fats and oils. With its ability to be used directly in existing diesel engines, biodiesel offers the immediate potential to reduce our demand for petroleum in the transportation sector.

- ✓ ***Leveraging limited supplies of fossil fuels….***
  Regardless of whose perspective one chooses to believe on the future supply of coal, oil and natural gas, it is indisputable that the supply of these fuels is, ultimately, limited. Biodiesel has the potential to leverage our use of limited supplies of fossil fuels.

- ✓ ***Mitigating greenhouse gas emissions….***
  The burning of fossil fuels over the past century has dramatically increased the levels of carbon dioxide ($CO_2$) and other "greenhouse gases" that trap heat in our atmosphere. The implications of the increasing levels of these greenhouse gases are a matter of serious debate. What is not questioned is that the levels of these greenhouse gases have risen at unprecedented rates in the context of geological time[1]. To the extent that biodiesel is truly renewable, it could play a role in reducing greenhouse gas emissions from the transportation sector.

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[1]Revelle published the groundbreaking work on atmospheric $CO_2$ build-up during the International Geophysical Year of 1957, in which he stated the problem of greenhouse gases more clearly than any researcher before or since. He stated that "Human beings are carrying out a large-scale geophysical experiment of a kind that could not have happened in the past nor be produced in the future. Within a few centuries, we are returning to the atmosphere and

- ✓ ***Reducing Air Pollution and Related Public Health Risks….*** One of EPA's primary charges is to reduce public health risks associated with environmental pollution. Biodiesel can play a role in reducing emissions of many air pollutants, especially those targeted by EPA in urban areas. These include emissions of particulate matter (PM), carbon monoxide (CO), hydrocarbons (HC), sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$) and air toxics.
- ✓ ***Benefiting our domestic economy….*** Spending on foreign imports of petroleum send dollars out of our economy. Biodiesel offers the potential to shift this spending from foreign imports to domestically produced energy. It also offers new energy-related markets to farmers.

## Why a life cycle study?

The purpose of this study is to quantify, to the extent possible, some of the benefits listed above. In this study, we have focused on those benefits related to biodiesel energy's balance, its effect on emissions of greenhouse gases, and its effects on the generation of air, water and solid waste pollutants. We have made no attempt to quantify domestic economic benefits of using biodiesel.

The effect of biodiesel on overall consumption of petroleum and other fossil fuels can only be understood in the context of this fuel's "life cycle"—the sequence of steps involved in making and using the fuel from the extraction of all raw materials from the environment to the final end-use of the fuel in an urban bus. Similarly, the accumulation of $CO_2$ in the atmosphere is a global effect that requires a comprehensive life cycle analysis. Furthermore, understanding the benefits of biodiesel means understanding how its life cycle emissions compare to those of petroleum diesel.

**This study provides a life cycle inventory of environmental and energy flows to and from the environment for both petroleum diesel and biodiesel, as well as for blends of biodiesel with petroleum diesel.**

## The scope of this study

Life cycle analysis is a complex science. The level of detail required in such a study forces a high degree of specificity in the scope and application of the products being studied. A substantial amount of information from engine tests and fuel demonstrations of soybean-derived biodiesel in urban buses is available. We relied on this recent data and experience to characterize the performance of soybean-derived biodiesel in this application.

## Findings

Conducting life cycle inventories is fraught with difficulties. Incomplete data is the rule rather than the exception. There are varying degrees of confidence in the results that we present in this report. The most reliable conclusions of this study are for overall energy balance and carbon dioxide emissions. For these two measures, our data is the most complete. More importantly, our sensitivity studies show that the estimates of carbon dioxide emissions and energy requirements are very robust-- that is, these results show little change in response to changes in key assumptions.

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the oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years." Revelle, R.; Suess, H. *Tellus*, Volume 9, No. 11, pp 18-21. 1957.

## Reductions in Petroleum and Fossil Energy Consumption

As one component of a strategy for reducing petroleum oil dependence and minimizing fossil fuel consumption, the use of biodiesel offers tremendous potential.

**Substituting 100% biodiesel (B100) for petroleum diesel in buses reduces the life cycle consumption of petroleum by 95%. This benefit is proportionate with the blend level of biodiesel used. When a 20% blend of biodiesel and petroleum diesel (B20) is used as a substitute for petroleum diesel in urban buses, the life cycle consumption of petroleum drops 19%.**

In our study, we found that the production processes for biodiesel and petroleum diesel are almost identical in their efficiency of converting a raw energy source (in this case, petroleum and soybean oil) into a fuel product. The difference between these two fuels is in the ability of biodiesel to utilize a renewable energy source.

**Biodiesel yields 3.2 units of fuel product energy for every unit of fossil energy consumed in its life cycle. The production of B20 yields 0.98 units of fuel product energy for every unit of fossil energy consumed.**

By contrast, petroleum diesel's life cycle yields only 0.83 units of fuel product energy per unit of fossil energy consumed. Such measures confirm the "renewable" nature of biodiesel.

## Reductions in $CO_2$ Emissions

Given the low demand for fossil energy associated with biodiesel, it is not surprising that biodiesel's life cycle emissions of $CO_2$ are substantially lower than those of petroleum diesel.

**Biodiesel reduces net emissions of $CO_2$ by 78.45% compared to petroleum diesel. For B20, $CO_2$ emissions from urban buses drop 15.66%.**

In addition, biodiesel provides modest reductions in total methane emissions, compared to petroleum diesel. Methane is another, even more potent, greenhouse gas. Thus, use of biodiesel to displace petroleum diesel in urban buses is an extremely effective strategy for reducing $CO_2$ emissions.

## Changes in Air Pollutant Emissions

The effect of biodiesel on air quality is more complex. Biodiesel, as it is available today, offers substantial improvements in some air pollutants, while it leads to increases in others.

## *Reductions in Particulates, Carbon Monoxide and Sulfur Oxides...*

**The use of B100 in urban buses results in substantial reductions in life cycle emissions of total particulate matter, carbon monoxide and sulfur oxides (32%, 35% and 8% reductions, respectively, relative to petroleum diesel's life cycle).**

All three of these pollutants have been targeted by EPA because of the important role they play in public health risks, especially in urban areas where the acute effects of these pollutants may be greater. Given the concern over urban air quality, it is important to note that most of these reductions occur because of lower emissions at the tailpipe. For buses operating in urban areas, this translates to an even greater potential benefit:

**Tailpipe emissions of particulates less than 10 microns in size are 68% lower for buses run on biodiesel (compared to petroleum diesel). In addition, tailpipe emissions of carbon monoxide are 46% lower for buses run on biodiesel (compared to petroleum diesel). Biodiesel completely eliminates emissions of sulfur oxides at the tailpipe.**

Tailpipe emissions of particulates that are smaller than 10 microns in size are specifically regulated by EPA because of the tendency for fine particulate matter to remain trapped in the lungs.

The reductions in air emissions reported here are proportional to the amount of biodiesel present in the fuel. Thus, for B20, users can expect to see 20% of the reductions reported for biodiesel used in its neat form (B100).

## *Increased Emissions of Nitrogen Oxides (NOx)…*

$NO_x$ is one of three pollutants implicated in the formation of ground level ozone and smog in urban areas ($NO_x$, CO and hydrocarbons).

**The use of B100 in urban buses increases life cycle emissions of $NO_x$ by 13.35%. Blending biodiesel with petroleum proportionately lowers $NO_x$ emission. B20 exhibits a 2.67% increase in life cycle emissions of $NO_x$. Most of this increase is directly attributable to increases in tailpipe emissions of $NO_x$. B100, for example, increases tailpipe levels of $NO_x$ by 8.89%.**

Our results are presented for fuel and engine technology as they exist today. Our study points out the need for research on both engine design and biodiesel fuel formulation to address this problem.

### *Hydrocarbons—higher on a life cycle basis, but lower at the tailpipe…*

The increase in hydrocarbon emissions is due to release of hexane in the processing of soybeans and volatilization of agrochemicals applied on the farm.

**Total life cycle emissions of hydrocarbons are 35% higher for B100, compared to petroleum diesel. However, emissions of hydrocarbons at the tailpipe are actually 37% lower.**

These results point out opportunities for improving the life cycle of biodiesel. Future biodiesel research should focus on ways of reducing hexane releases from today's current levels in soybean crushing plants. Improvements in use of agrochemicals on the farm would have similarly beneficial effects.

## Next Steps

At the outset, we designed this study to identify and quantify the advantages of biodiesel as a substitute for petroleum diesel. These advantages are substantial, especially in the area of energy security and control of greenhouse gases. We have also identified weaknesses or areas of concern for biodiesel—such as its emissions of $NO_x$ and hydrocarbons. We see these as opportunities for further research to resolve these concerns. We hope that our findings will be used to focus future biodiesel research on these critical issues.

There is much that could be done to build on and improve the work we have done here. Appropriate next steps for this work include the following:

- **Use the life cycle inventory to assess the relative effects of petroleum diesel and biodiesel on our environment and on public health risks in order to gain an understanding of the benefits associated with biodiesel.**
- **Quantify the costs and benefits of biodiesel.**
- **Assess the economic impact of biodiesel as an alternative fuel (e.g., its effects on jobs, trade deficit, etc.)**
- **Evaluate other feedstock sources.**
- **Incorporate new health effects data on hydrocarbon emissions from biodiesel and petroleum diesel.**
- **Develop regional life cycle models for biodiesel use.**
- **Evaluate performance of newer diesel engines and new fuel production technologies.**

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# 1 How To Use This Report

Reporting on the results of a life cycle study is at best an awkward process. The complexity of such a study can lead to the necessary, but sometimes tedious, reporting of much detail. For life cycle analysis, the devil is truly in the details.

We recognize, however, that there are many types of readers who may find an interest in the results of our work. Therefore, we have presented our study at three different levels of detail: one for the policymaker interested in “cutting to the quick,” one for the more technically oriented staff often supporting policy decisions, and one for the “hard core” life cycle practitioner. This approach has undoubtedly led to some redundancy in our presentation. We apologize for any inconvenience that this may cause, but hope that (at least for those who bothered to stop here first before diving into the report) most will find this approach more economical in targeting the appropriate level of detail needed.

Here is a road map for finding your way around this report:

***For a quick and concise description of the study and its results, see…***

- Executive Summary (starting on page iii)

***For the 2nd level of detail providing more information on how we conducted the study and a more detailed discussion of results, see…***

- Section 1.0 Technical Overview. This overview is can be read without any need to reference later sections (including the bibliography at the end).

***For the “hard core” details of our modeling and a detailed discussion of the results see…***

- Section 2.0 through Section 11.0. The reader can start from section 2.0 to get a complete and detailed description of the study.

Each of the three levels described above is essentially free standing and can be read independently to get a full perspective on the study.

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# 2 Technical Overview

This report presents the findings from a study of the life cycle inventories (LCIs) for petroleum diesel and biodiesel. An LCI is a comprehensive quantification of all the energy and environmental flows associated with a product from "cradle to grave." It provides information on:

- Raw materials extracted from the environment
- Energy resources consumed
- Air, water, and solid waste emissions generated.

By "cradle to grave," we mean all the steps from the first extraction of raw materials from the environment to the final end-use of the product. LCIs are invaluable tools for assessing and comparing the overall environmental impacts of various products. One purpose for conducting this study is to assess overall greenhouse gas emissions from these two fuels. Because of the global nature of greenhouse gas effects, these emissions lend themselves very well to life cycle assessment (LCA). We also considered other environmental emissions; particularly regulated air emissions such as carbon monoxide, hydrocarbons, nitrogen oxides, sulfur oxides and particulate matter. The purpose of this study is to provide LCI data that can be used by industry and government decision-makers considering biodiesel as an alternative fuel. This study is the product of a highly effective partnership between the U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE), which has brought together the agricultural and energy expertise needed to adequately address an LCI of biodiesel.

## 2.1 Stakeholder Involvement

Any good life cycle study makes use of every opportunity to obtain input from all who have a stake in the final outcome. This is especially true for those life cycle studies being conducted to support important government policy decisions. Many of the early decisions made in setting the scope of the study (see section 2.2) can have a profound effect on the outcome of the study. This makes it crucial that all stakeholders have an opportunity to discuss the key assumptions and options for the analysis. But stakeholder involvement cannot stop there. Input throughout the major steps of the project is useful for ensuring the proper use and interpretation of the best available data. Finally, as results from the LCI model become available, offering the opportunity to have stakeholders provide their perspective helps to avoid "tunnel vision." The most important reason for stakeholder involvement in the study is *credibility*. When such studies are done in a vacuum, they stand little chance of getting buy-in from the industries involved. In the end, LCI results are only as good as the "buy-in" or level of credibility they engender.

We made stakeholder involvement a top priority in our study. The following is a list of the groups that provided input to us during the project:

- Petroleum Industry
- Oilseed Processing Industry
- Animal Renderers and Recyclers
- Chemical Process Industry

- Biodiesel Producers
- Engine Manufacturers
- U.S. Department of Agriculture
- U.S. Department of Energy
- U.S. Environmental Protection Agency
- State and Local Governments
- Environmental Public Interest Groups.

Outlined below is a brief description of the process used to continually check in with stakeholders. Throughout this process, we provided opportunities to communicate with us in writing, by phone, and by e-mail, as well as in our face-to-face meetings.

1. Before pen was put to paper, USDA and DOE brought together a consortium of stakeholders at a meeting hosted by USDA in Washington, DC, to discuss the need and goals of our study.
2. Based on input from this group, a preliminary scoping document was put together and distributed for review.
3. A second face-to-face meeting with stakeholders was held to work out the details of the project scope.
4. Once the basic data had been collected on all aspects of the petroleum diesel and biodiesel life cycles, the stakeholders reconvened to review the data. Feedback from this meeting resulted in our updating data sources and filling in gaps in available data.
5. Finally, once results from the LCI model were available, we sought detailed comments from a representative group of stakeholders (that is, those willing to put in the time to study our results). They were given a first draft of this report. Their comments have been carefully compiled. Wherever possible, we have made changes to the model and the report to reflect concerns and criticisms raised by this group. This document is a product of that final review.

The quality of our results is much the better for the input of these groups. We are indebted to the individuals who took the time to participate in this process.

## 2.2 Scope of the Life Cycle Study

### 2.2.1 Purpose

The purpose of this study is to conduct an LCI to quantify and compare the comprehensive sets of environmental flows (to and from the environment) associated with both biodiesel and petroleum-based diesel, over their entire life cycles. In addition to the purpose stated, this LCA was initiated to provide the necessary information that could be used to answer the following questions that have been posed by policy makers:

### 2.2.2 What Is "Biodiesel?"

In its most general sense, "biodiesel" has been used to refer to any diesel fuel substitute that is derived from renewable biomass. In the past few years, biodiesel has taken on a more specific definition and currently refers to a family of products made from vegetable oils or animal fats and alcohol, such as methanol or ethanol. These are called alkyl esters of fatty acids. In order for these alkyl esters of fatty acids to be considered as viable transportation fuels, they must meet stringent quality standards, otherwise they become standard industrial chemicals that are not suitable for diesel applications. Thus, alkyl esters of fatty acids that meet transportation fuel standards are called "biodiesel." One popular process for producing biodiesel is known as "transesterification." This is the technology modeled in this report.

Today, biodiesel is made from a variety of natural oils. Chief among these are soybean oil and rapeseed oil. Rapeseed oil, a close cousin of canola oil, dominates the growing biodiesel industry in Europe. In the United States, biodiesel is being made from soybean oil because more soybean oil is produced than all other sources of fats and oil combined. There are many candidates for feedstocks, including recycled cooking oils, animal fats, and a variety of other oilseed crops. We selected soybean oil as the feedstock used for biodiesel production because of the vast number of data that have been generated about biodiesel from soybean oil.

Today, the most widely used alcohol for biodiesel production is methanol, mostly because of its ease of processing and its relatively low cost. We have chosen to model biodiesel production using methanol. Thus, the working definition of biodiesel in our study is a diesel fuel substitute made via the transesterification of soybean oil with methanol. In industry parlance, this biodiesel product is referred to as soy methyl ester or methyl soyate.

### 2.2.3 What Is "Petroleum Diesel?"

We defined petroleum diesel as "on-highway" low-sulfur diesel made from crude oil. Recent regulations promulgated by the U.S. Environmental Protection Agency (EPA) as part of its enforcement of the 1990 Clean Air Act Amendments set tougher restrictions on diesel used on the road versus diesel used off the road. The "on highway" diesel must now meet new limits for sulfur content that are an order of magnitude lower than previously allowed (0.05 wt% versus 0.5% sulfur). We restrict our evaluation of petroleum diesel to this new low-sulfur diesel[2].

### 2.2.4 Defining the Product Application

The choice of the fuels' end-use can greatly affect the life cycle flows. Potential markets for biodiesel cover a wide range of diesel applications, including most truck operations, stationary generation, mining equipment, marine diesel engines, and bus fleets. In this study, we compare the use of petroleum diesel and biodiesel in urban buses. This choice was based on the availability of end-use data. The urban bus market was identified by the nascent U.S. biodiesel industry early on as a near-term opportunity, and a large number of data are available on the performance of diesel bus engines.

### 2.2.5 What Is Included in the Life Cycle Systems?

Major operations included within the boundary of the petroleum diesel system are:

- Extraction of crude oil from the ground
- Transport of crude oil to an oil refinery
- Refining of crude oil to diesel fuel
- Transport of diesel fuel to its point of use
- Use of the fuel in a diesel bus engine.

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[2] One important clarification should be made about our characterization of petroleum diesel. In our analysis, low-sulfur diesel fuel is used in the product application (urban buses). This is not true for agricultural use of diesel fuel in the production of soybeans. Data for "off highway" diesel-powered tractors were used to characterize performance and emissions of these engines. This off-highway diesel is not held to the same strict standard for sulfur content.

For the biodiesel system, major operations include:

- Produce soybeans
- Transport soybeans to a soy crushing facility
- Recover soybean oil at the crusher
- Transport soybean oil to a biodiesel manufacturing facility
- Conversion of soybean oil to biodiesel
- Transport biodiesel fuel to the point of use
- Use the fuel in a diesel bus engine.
- These operations are not a comprehensive list of what has been modeled in our analysis. These operations include within them detailed processes described elsewhere in this report. For example, extraction of crude oil includes flows from a number of operations such as onshore and offshore drilling and natural gas separation. Onshore drilling is further characterized as either conventional or advanced technology.

We include more than just the energy and environmental flows that occur directly in each of these steps. Energy and environmental inputs from the production of any raw materials used in each step are also included. Generally, life cycle flows are characterized for all raw materials from the point of extracting their primary components from the environment. For example, methanol use in the biodiesel manufacturing facility contributes life cycle flows that go back to the extraction of natural gas used as a feedstock. Likewise, life cycle flows from intermediate energy sources such as electricity are included—back to extraction of coal, oil, natural gas, limestone, and any other primary resources needed.

### 2.2.6 What Are the Geographical Boundaries?

The LCA is limited to the use of petroleum diesel and biodiesel in the United States. This does not mean that all the steps involved in the life cycles are restricted to domestic boundaries. Petroleum diesel's life cycle, in particular, expands its geographic limits to include foreign crude oil production simply because half the crude oil used in the United States is imported. Other aspects of the geographic limits of the study involve the choice of national versus regional or even site-specific assessment. For domestic operations, we rely on national average data. For foreign operations, we rely on industry average data. Electricity generation is modeled on a national basis. Table 1 and Table 2 present specific information on the geographical scope of the analysis for each stage of the petroleum diesel and biodiesel life cycles.

### 2.2.7 What Is the Time Frame?

We were faced with two basic options: 1) model technology and markets as they are today; and 2) model a futuristic scenario based on projected technology and markets. We chose to focus on a current time frame. Thus, we consider production and end-use technologies that are available today for both petroleum diesel and biodiesel. This approach ignores future advances in production efficiency and end-use engine technology. By limiting the analysis to the present, it is far more "grounded" and objective because it relies on documented data rather than on potentially optimistic projections. Results from this study provide a baseline for considering future scenarios.

### 2.2.8 Basis for Comparing the Life Cycles

Common sense suggests that any comparison of two fuel products must be done on the same basis. In the lexicon of LCA, two industrial systems are compared on the same "functional basis." In other words, the fuels are compared based on identical services they provide. Once this shared function is defined, a unit has to be chosen in order to compare the systems on the same quantitative basis. For example, a comparison of fuel life cycles for passenger vehicles might characterize all life cycle flows per mile of travel delivered by the vehicle.

The unit used to normalize all life cycle flows is known as the "functional unit." For a more detailed discussion of the definition and protocols established for LCIs, refer to publications from the Society of Environmental Toxicology and Chemistry (SETAC)[3] and EPA[4]. Medium- and heavy-duty diesel engines are typically evaluated on the basis of actual work delivered by the engine. This approach is used because of the variability (or even the irrelevance) of mileage among the various applications for diesel engines. Therefore, we have chosen to compare the life cycle flows of biodiesel and petroleum diesel on the basis of 1 brake horsepower-hour (bhp-h) of work delivered by the bus engine.

**Table 1: Geographic Scope of the Petroleum Diesel Life Cycle**

| Life Cycle Stage | Geographic Scope |
|---|---|
| Crude Oil Extraction | International average based on the consumption of crude oil in the United States |
| Crude Oil Transportation | International average transportation distances to the United States |
| Crude Oil Refining | U.S. national average |
| Diesel Fuel Transportation | U.S. national average |
| Diesel Fuel Use | U.S. national average based on urban bus use |

**Table 2: Geographic Scope of the Biodiesel Life Cycle**

| Life Cycle Stage | Geographic Scope |
|---|---|
| Soybean Agriculture | Average based on data from the 14 key soybean-producing states |
| Soybean Transportation | U.S. national average |
| Soybean Crushing | U.S. national average based on modeling of a generic U.S. crushing facility |
| Soybean Oil Transport | U.S. national average |
| Soybean Oil Conversion | U.S. average based on modeling of a generic biodiesel facility |
| Biodiesel Transportation | U.S. national average |
| Biodiesel Fuel Use | U.S. national average based on urban bus use |

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[3] SETAC, *A Technical Framework for Life-Cycle Assessments,* Society of Environmental Toxicology and Chemistry, Washington DC, 1991; SETAC, *Guidelines for Life-Cycle Assessment: A "Code of Practice,"* Society of Environmental Toxicology and Chemistry, Washington, DC, 1993; SETAC, *A Conceptual Framework for Life-Cycle Impact Assessment,* Society of Environmental Toxicology and Chemistry, Washington, DC, 1993; SETAC, *Life Cycle Assessment Data Quality: A Conceptual Framework*, Society of Environmental Toxicology and Chemistry, Washington ,DC, 1994.

[4] EPA: *Life Cycle Design Manual: Environmental Requirements and the Product System,* EPA/600/R-92/226, 1993; U.S. Environmental Protection Agency, *Life-Cycle Assessment: Inventory Guidelines and Principles*, EPA/600-R-92-245, 1993; U.S. Environmental Protection Agency, *Guidelines for Assessing the Quality of Life-Cycle Inventory Analysis,* EPA/530-R-95-010, 1995.

## 2.3 Key Assumptions

The details of the assumptions and modeling steps of the life cycle are presented in subsequent sections of this report, although two general assumptions applied in the modeling should be highlighted. First, national average distances were used for transport of all feedstocks, intermediates, and products. The effect of this assumption was tested in a sensitivity analysis. Second, both fuels are assumed to be used in "current" diesel engines, defined as engines calibrated to meet 1994 EPA regulations for diesel exhaust when operated on low-sulfur petroleum diesel. Other assumptions worth noting include:

- Crude oil delivery from domestic and foreign sources are split almost evenly
- Best available refinery data for extant facilities were used to model a "generic" refinery
- Emissions from petroleum diesel are assumed to meet 1994 engine emissions standards.
- Biodiesel assumptions worth noting include:
- Agriculture practices and yields are based on weighted averages for 14 soybean-producing states
- Emissions are based on actual engine data for biodiesel emissions that are then modeled as changes in the oxygen content[5] in the fuel
- Energy efficiencies of biodiesel-fueled engines are identical to those of petroleum diesel-fueled engines[6]
- Biomass-derived carbon dioxide ($CO_2$) in the fuel emissions is recycled in soybean production.

For details on the bases for these assumptions, refer to the sections describing each stage of the life cycles.

## 2.4 Findings

LCI results are presented for 100% biodiesel (known as "B100"), a 20% blend of biodiesel with petroleum diesel (known as "B20"), and petroleum diesel. These results include estimates of:

- Overall energy requirements
- $CO_2$ emissions
- Other regulated and non-regulated air emissions. Regulated pollutants include carbon monoxide (CO), particulate matter less than 10 microns in size (PM10), non-methane hydrocarbons (NMHC), and nitrogen oxides ($NO_x$). Non-regulated air emissions include methane ($CH_4$), formaldehyde, benzene, total hydrocarbons (THC), and total particulate matter (TPM).
- Water emissions
- Solid wastes.

These life cycle flows are presented for the base-case scenarios and for two sensitivity studies. The base case describes petroleum diesel and biodiesel life cycle flows for "national average" scenarios.

The purpose of conducting sensitivity studies on the life cycle of biodiesel was to establish the potential range for improvement in the fuel, as well as to establish the range of possible error associated with the

[5] Diesel fuel contains no oxygen. The amount of oxygen is a measure of biodiesel content in the fuel. In addition, percent oxygen proves to be a good basis for predicting emissions.

[6] This is substantiated with an analysis of engine performance data.

assumptions made in the model. The LCI assumes a "current" time frame—that is, we are looking at options for improvement of agriculture, soybean oil recovery, conversion technology, and engine technology within a short-term horizon. This sets realistic limitations on the assumptions used in the model.

In each life cycle step we considered the potential for near-term improvement. Two main areas were identified. First, we felt it was important to understand the impact of location on biodiesel production. This allows us to consider the benefits of the best agricultural productivity available in the United States and the shortest distances for transport of fuel and materials. This sets an upper bound on biodiesel benefits from the perspective of current agricultural practices and transportation logistics.

Second, we identified the conversion of soybean oil to biodiesel as an aspect of the life cycle that has significant impact on energy use and emissions and that has a broad range of efficiencies, depending on the commercial technology used. Our base case estimate of the energy requirements for soy oil conversion is based on a preliminary engineering design prepared for this study. The design was loosely based on data from an extant transesterification plant in Kansas City, Missouri. Our energy budget proved to be much lower than that reported for the facility in Kansas City. A review of the literature on recent transesterification technology revealed that our design estimate is at the high end of the range of recently published literature values. To deal with this disparity in energy estimates for conversion of soy oil to biodiesel, we decided to look at the range of reported energy budgets as a sensitivity study.

Changes in engine technology may also be an avenue for improving biodiesel on a life cycle basis. We opted to forego this area in our sensitivity analysis because of limited data. Thus, we present in this report the results of two sensitivity studies:

- The base case for B100 is compared with the LCI for an optimal biodiesel location (Chicago). The choice of an optimal location is based on an evaluation of regions with the most efficient production of soybeans, local concentration of soybean producers, and large end-use markets for urban buses.
- Results for a range of high and low energy demands for soybean conversion to biodiesel are compared to determine the impact of this stage of the biodiesel life cycle on overall emissions and energy flows. Low and high values for energy consumption were based on a survey of technical literature on the most recent technologies commercially available.

### 2.4.1 Results of the Base Case Study

The results provided here allow the reader to make a nominal comparison of biodiesel and petroleum diesel. By nominal, we mean that the LCIs calculated for each fuel reflect generic "national average" models. The only exception to this statement is soybean agriculture data, which are provided on a state-by-state basis for the 14 key soybean-producing states. Implicit in such a nominal comparison is that there are no regional differences that could affect any of the stages of each fuel's life cycle. There will, of course, be differences that will affect each fuel.

In most cases, biodiesel is interchangeable with petroleum diesel without any need to modify today's diesel engine. However, one key issue for biodiesel use that should be explicitly is the effect of regional climate on the performance of the fuel. This fuel's cold flow properties may limit its use in certain parts of the country during the winter. This caveat should be kept in mind. Means of mitigating biodiesel's cold flow properties are being evaluated by researchers, though no clear solution is at hand. Low-sulfur #2 diesel fuel has similar limitations that are currently addressed with the use of additives and by blending this fuel with #1 diesel fuel.

#### 2.4.1.1 Life Cycle Energy Balance

LCIs provide an opportunity to quantify the total energy demands and the overall energy efficiencies of processes and products. Understanding the overall energy requirements of biodiesel is key to our understanding the extent to which biodiesel made from soybean oil is a "renewable energy" source. Put quite simply, the more fossil energy required to make a fuel, the less we can say that this fuel is "renewable". Thus, the renewable nature of a fuel can vary across the spectrum of "completely renewable." (i.e., no fossil energy input) to nonrenewable (i.e., fossil energy inputs as much or more than the energy output of the fuel)[7]. Energy efficiency estimates help us to determine how much additional energy must be expended to convert the energy available in raw materials used in the fuel's life cycle to a useful transportation fuel. The following sections describe these basic concepts in more detail, as well as the results of our analysis of the life cycle energy balances for biodiesel and petroleum diesel.

##### *2.4.1.1.1 Types of Life Cycle Energy Inputs*

In this study, we track several types of energy flows through each fuel life cycle. For clarity, each of these energy flows is defined below.

- *Total Primary Energy*. All raw materials extracted from the environment can contain[8] energy. In estimating the total primary energy inputs to each fuel's life cycle, we consider the cumulative energy content of all resources extracted from the environment.
- *Feedstock Energy*. Energy contained in raw materials that end up directly in the final fuel product is termed "feedstock energy." For biodiesel production, feedstock energy includes the energy contained in the soybean oil and methanol feedstocks that are converted to biodiesel. Likewise, the petroleum directly converted to diesel in a refinery contains primary energy that is considered a feedstock energy input for petroleum diesel. Feedstock energy is a subset of the primary energy inputs.
- *Process Energy*. The second major subset of primary energy is "process energy." This is limited to energy inputs in the life cycle exclusive of the energy contained in the feedstock (as defined in the previous bullet). It is the energy contained in raw materials extracted from the environment that does not contribute to the energy of the fuel product itself, but is needed in the processing of feedstock energy into its final fuel product form. Process energy consists primarily of coal, natural gas, uranium, and hydroelectric power sources consumed directly or indirectly in the fuel's life cycle.
- *Fossil Energy*. Because we are concerned about the renewable nature of biodiesel, we also track the primary energy that comes from fossil sources specifically (coal, oil, and natural gas). All three of the previously defined energy flows can be categorized as fossil or nonfossil energy.
- *Fuel Product Energy*. The energy contained in the final fuel product, which is available to do work in an engine, is what we refer to as the "fuel product energy". All other things being equal, fuel product energy is a function of the energy density of each fuel.

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[7] This last statement is an oversimplification. We consider the energy trapped in soybean oil to be renewable because it is solar energy stored in liquid form through biological processes that are much more rapid than the geologic time frame associated with fossil energy formation. Also, other forms of nonrenewable energy besides fossil fuel exist.

[8] The energy "contained" in a raw material is the amount of energy that would be released by the complete combustion of that raw material. This "heat of combustion" can be measured in two ways: as a higher heating value or a lower heating value. Combustion results in the formation of $CO_2$ and water. Higher heating values consider the amount of energy released when the final combustion products are gaseous $CO_2$ and liquid water. Lower heating values take into account the loss of energy associated with the vaporization of the liquid water combustion product. Our energy content is based on the lower heating values for each material.

### 2.4.1.1.2 Defining Energy Efficiency

We report two types of energy efficiency. The first is the overall "life cycle energy efficiency". The second is what we refer to as the "fossil energy ratio". Each elucidates a different aspect of the life cycle energy balance for the fuels studied.

The calculation of the life cycle energy efficiency is simply the ratio of fuel product energy to total primary energy:

Life Cycle Energy Efficiency = Fuel Product Energy/Total Primary Energy

It is a measure of the amount of energy that goes into a fuel cycle, which actually ends up in the fuel product. This efficiency accounts for losses of feedstock energy and additional process energy needed to make the fuel.

The fossil energy ratio tells us something about the degree to which a given fuel is or is not renewable. It is defined simply as the ratio of the final fuel product energy to the amount of fossil energy required to make the fuel:

Fossil Energy Ratio = Fuel Energy/Fossil Energy Inputs

If the fossil energy ratio has a value of zero, then a fuel is not only completely nonrenewable, but it provides no useable fuel product energy as a result of the fossil energy consumed to make the fuel. If the fossil energy ratio is equal to 1, then this fuel is still nonrenewable. A fossil energy ratio of one means that no loss of energy occurs in the process of converting the fossil energy to a useable fuel. For fossil energy ratios greater than 1, the fuel actually begins to provide a leveraging of the fossil energy required to make the fuel available for transportation. As a fuel approaches being "completely" renewable, its fossil energy ratio approaches "infinity." In other words, a completely renewable fuel has no requirements for fossil energy.

From a policy perspective, these are important considerations. Policymakers want to understand the extent to which a fuel increases the renewability of our energy supply. Another implication of the fossil energy ratio is the question of climate change. Higher fossil energy ratios imply lower net $CO_2$ emissions. This is a secondary aspect of the ratio, as we are explicitly estimating total $CO_2$ emissions from each fuel's life cycle. Nevertheless, the fossil energy ratio serves as a check on our calculation of $CO_2$ life cycle flows (since the two should be correlated).

### 2.4.1.1.3 Petroleum Diesel Life Cycle Energy Consumption

Table 3 and Figure 1 show the total primary energy requirements for the key steps in the production and use of petroleum diesel. The LCI model shows that 1.2007 MJ of primary energy is used to make 1 MJ of petroleum diesel fuel. This corresponds to a life cycle energy efficiency of 83.28%[9].

The distribution of the primary energy requirements for each stage of the petroleum diesel life cycle is shown in Table 3. In Figure 1, the stages of petroleum diesel production are ranked from highest to lowest in terms of primary energy demand. Ninety-three percent of the primary energy demand is for extracting crude oil from the ground. About 88% of the energy shown for crude oil extraction is associated with the energy value of the crude oil itself. The crude oil refinery step for making diesel fuel dominates the remaining 7% of the primary energy use.

Removing the feedstock energy of the crude itself from the primary energy total allows us to analyze the relative contributions of the process energy used in each life cycle. Process energy used in each stage of the petroleum life cycle is shown in Figure 2. Process energy demand represents 20% of the energy

[9] Using the total primary energy reported in Table 3, Life Cycle Energy Efficiency = 1 MJ of Fuel Product Energy/1.2007 MJ of Primary Energy Input = 0.8328.

ultimately available in the petroleum diesel fuel product. About 90% of the total process energy is in refining (60%) and extraction (29%). The next largest contribution to total process energy is for transporting foreign crude oil to domestic petroleum refiners.

**Table 3: Primary Energy Requirements for the Petroleum Diesel Life Cycle**

| Stage | Primary Energy (MJ per MJ of Fuel) | Percent |
|---|---|---|
| Domestic Crude Production | 0.5731 | 47.73% |
| Foreign Crude Oil Production | 0.5400 | 44.97% |
| Domestic Crude Transport | 0.0033 | 0.28% |
| Foreign Crude Transport | 0.0131 | 1.09% |
| Crude Oil Refining | 0.0650 | 5.41% |
| Diesel Fuel Transport | 0.0063 | 0.52% |
| Total | 1.2007 | 100.00% |

There are some significant implications in the process energy results shown in Figure 2 regarding trends for foreign and domestic crude oil production and use. Transportation of foreign crude oil carries with it a fourfold penalty for energy consumption compared to domestic petroleum transport because the overseas transport of foreign oil by tanker increases the travel distance for foreign oil by roughly a factor of four.

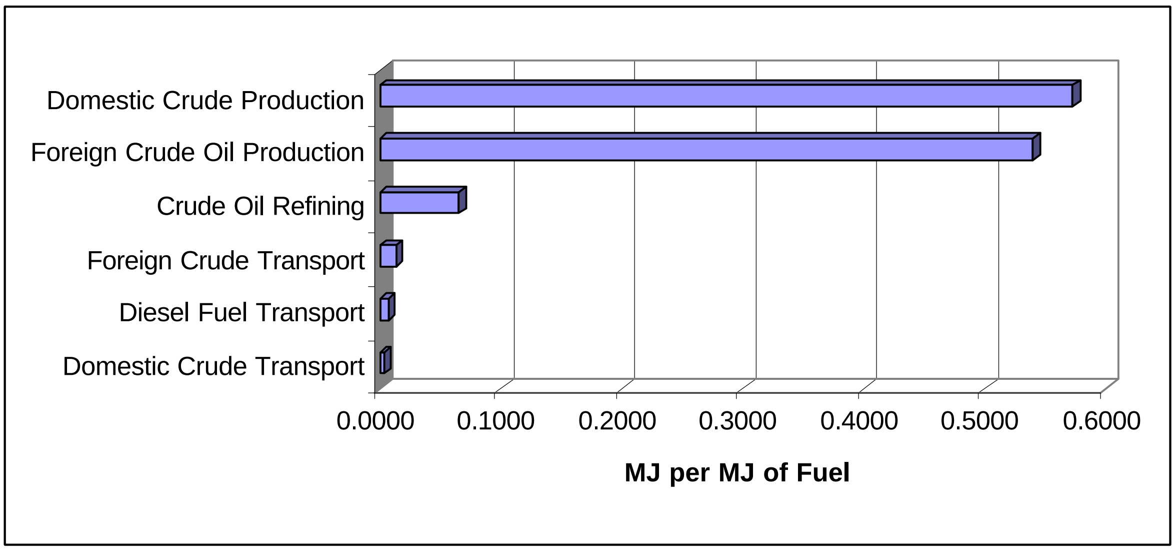


**Figure 1: Ranking of Primary Energy Demand for the Stages of Petroleum Diesel Production**

At the same time, domestic crude oil extraction is more energy intensive than foreign crude oil production. Advanced oil recovery practices in the United States represent 11% of the total production volume, compared to 3% for foreign oil extraction. Advanced oil recovery uses twice as much primary energy per kilogram of oil compared to conventional extraction. Per kilogram of oil out of the ground, advanced crude oil extraction requires almost 20 times more process energy than onshore domestic crude oil extraction because the processes employed are energy intensive and the amount of oil recovered is low compared to other practices. Domestic crude oil supply is essentially equal to foreign oil supply (50.26% versus 49.74%, respectively) in our model, but its process energy requirement is 62% higher than that of foreign crude oil production (see Figure 2).

If our present trend of increased dependence on foreign oil continues, we can expect the life cycle energy efficiency of petroleum diesel to worsen because of the higher energy costs of transporting foreign crude to the United States. In addition, with declining domestic oil supplies, we may well see increased energy penalties for domestic crude oil extraction, as the practice of advanced oil recovery increases.

Table 4 and Figure 3 summarize the fossil energy inputs with respect to petroleum diesel's energy output. Petroleum diesel uses 1.1995 MJ of fossil energy to produce 1 MJ of fuel product energy. This corresponds to a fossil energy ratio of 0.8337[10]. Because the main feedstock for diesel production is itself a fossil fuel, it is not surprising that this ratio is almost identical to the life cycle energy efficiency of 83.28%. In fact, fossil energy associated with the crude oil feedstock accounts for 93% of the total fossil energy consumed in the life cycle. The fossil energy ratio is slightly less than the life cycle energy ratio because there is a very small contribution to the total primary energy demand, which is met through hydroelectric and nuclear power supplies related to electricity generation.

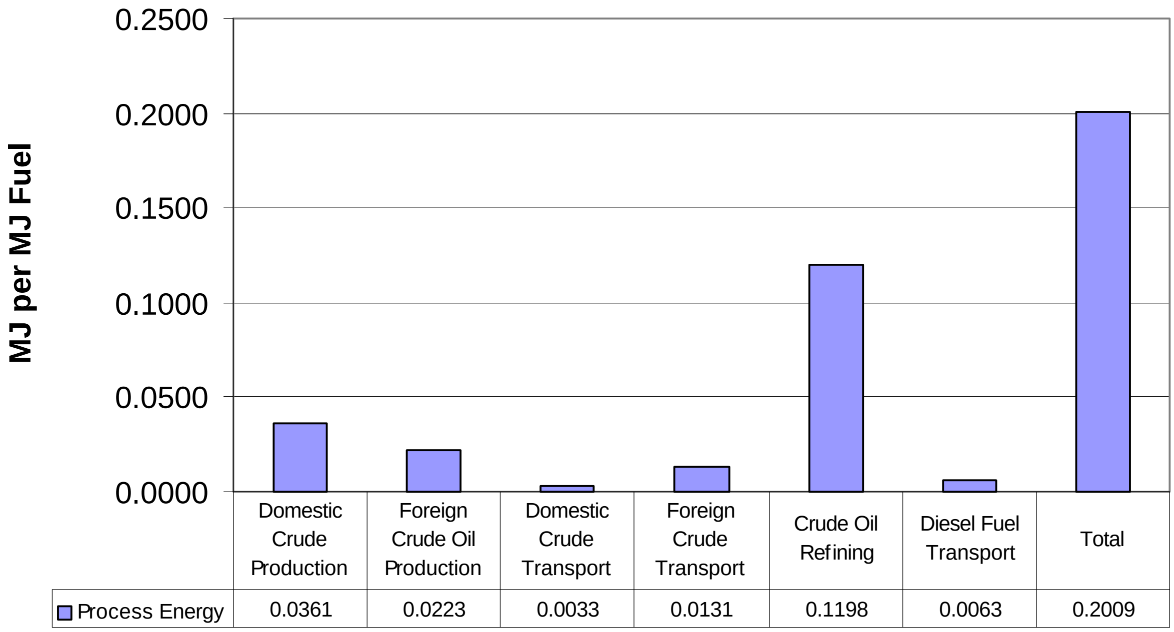


**Figure 2: Process Energy Demand for Petroleum Diesel Life Cycle**

### *2.4.1.1.4 Biodiesel Life Cycle Energy Demand*

Table 5 and Figure 4 present the total primary energy demand used in each stage of the biodiesel life cycle. One MJ of biodiesel requires an input of 1.2414 MJ of primary energy, resulting in a life cycle energy efficiency of 80.55%. Biodiesel is comparable to petroleum diesel in the conversion of primary energy to fuel product energy (80.55% versus 83.28%). The largest contribution to primary energy (87%) is the soybean oil conversion step because this is where we have chosen to include the feedstock energy

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[10] Fossil Energy Ratio = 1 MJ Fuel Energy/1.1995 MJ of Fossil Energy Input = 0.8337.

associated with the soybean oil itself[11]. As with the petroleum life cycle, the stages of the life cycle that are burdened with the feedstock energy overwhelm all other stages. Had the soybean oil energy been included with the farming operation, then soybean agriculture would have been the dominant consumer of primary energy. This is analogous to placing the crude oil feedstock energy in the extraction stage for petroleum diesel fuel. The next two largest primary energy demands are for soybean crushing and soybean oil conversion. They account for most of the remaining 13% of the total demand.

**Table 4: Fossil Energy Requirements for the Petroleum Diesel Life Cycle**

| Stage | Fossil Energy (MJ per MJ of Fuel) | Percent |
|---|---|---|
| Domestic Crude Production | 0.572809 | 47.75% |
| Foreign Crude Oil Production | 0.539784 | 45.00% |
| Domestic Crude Transport | 0.003235 | 0.27% |
| Foreign Crude Transport | 0.013021 | 1.09% |
| Crude Oil Refining | 0.064499 | 5.38% |
| Diesel Fuel Transport | 0.006174 | 0.51% |
| Total | 1.199522 | 100.00% |

When we look at process energy separately from primary energy, we see that energy demands in the biodiesel life cycle are not dominated by soybean oil conversion (Figure 5). The soybean crushing and soy oil conversion to biodiesel demand the most process energy (34.25 and 34.55%, respectively, of the total demand). Agriculture accounts for most of the remaining process energy consumed in life cycle for biodiesel (almost 25% of total demand). Each transportation step is only 2%-3% of the process energy used in the life cycle.

[11] Energy contained in the soybean oil itself represents, in effect, the one place in the biodiesel life cycle where input of solar energy is accounted for. Total radiant energy available to soybean crops is essentially viewed as “free” in the life cycle calculations. It becomes an accountable element of the life cycle only after it has been incorporated in the soybean oil itself. This is analogous to counting the feedstock energy of crude petroleum as the point in its life cycle where solar energy input occurs. Petroleum is essentially stored solar energy. The difference between petroleum and soybean oil as sinks for solar energy is their time scale. While soybean oil traps solar energy on a rapid (“real time”) basis, petroleum storage represents a process that occurs on a geologic time scale. This difference in the dynamic nature of solar energy utilization is the key to our definitions of renewable and nonrenewable energy.

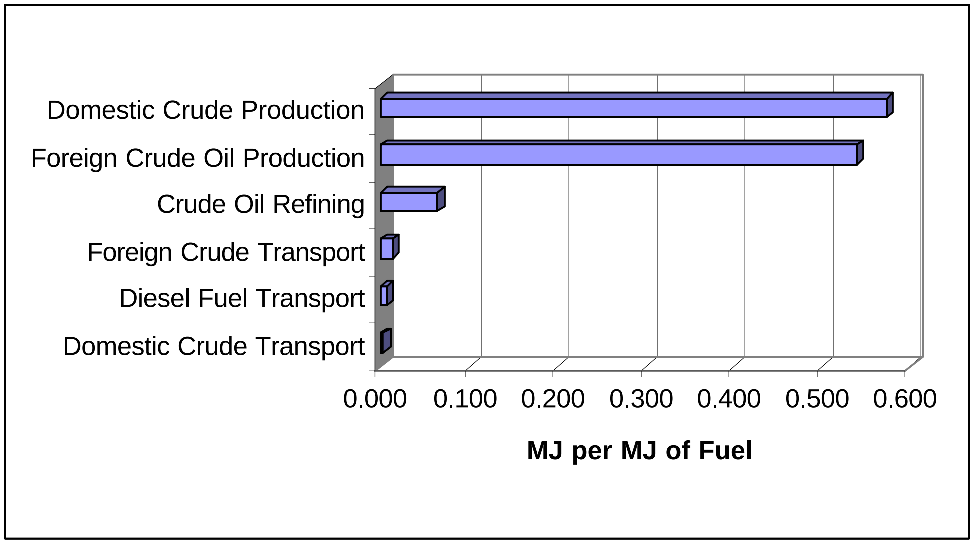


**Figure 3: Ranking of Fossil Energy Demand for Stages of the Petroleum Diesel Life Cycle**

**Table 5: Primary Energy Requirements for Biodiesel Life Cycle**

| Stage | Primary Energy (MJ per MJ of Fuel) | Percent |
|---|---|---|
| Soybean Agriculture | 0.0660 | 5.32% |
| Soybean Transport | 0.0034 | 0.27% |
| Soybean Crushing | 0.0803 | 6.47% |
| Soy Oil Transport | 0.0072 | 0.58% |
| Soy Oil Conversion | 1.0801 | 87.01% |
| Biodiesel Transport | 0.0044 | 0.35% |
| Total | 1.2414 | 100.00% |

Table 6 and Figure 6 summarize the fossil energy requirements for the biodiesel life cycle. Because 90% of its feedstock requirements are renewable (that is, soybean oil), biodiesel's fossil energy ratio is favorable. Biodiesel uses 0.3110 MJ of fossil energy to produce one MJ of fuel product; this equates to a fossil energy ratio of 3.215. In other words, the biodiesel life cycle produces more than three times as much energy in its final fuel product as it uses in fossil energy. Fossil energy demand for the conversion step is almost twice that of its process energy demand, making this stage of the life cycle the largest contributor to fossil energy demand. The use of methanol as a feedstock in the production of biodiesel accounts for this high fossil energy demand. We have counted the feedstock energy of methanol coming into the life cycle at this point, assuming that the methanol is produced from natural gas. This points out an opportunity for further improvement of the fossil energy ratio by substituting natural gas-derived methanol with renewable sources of methanol, ethanol or other alcohols.

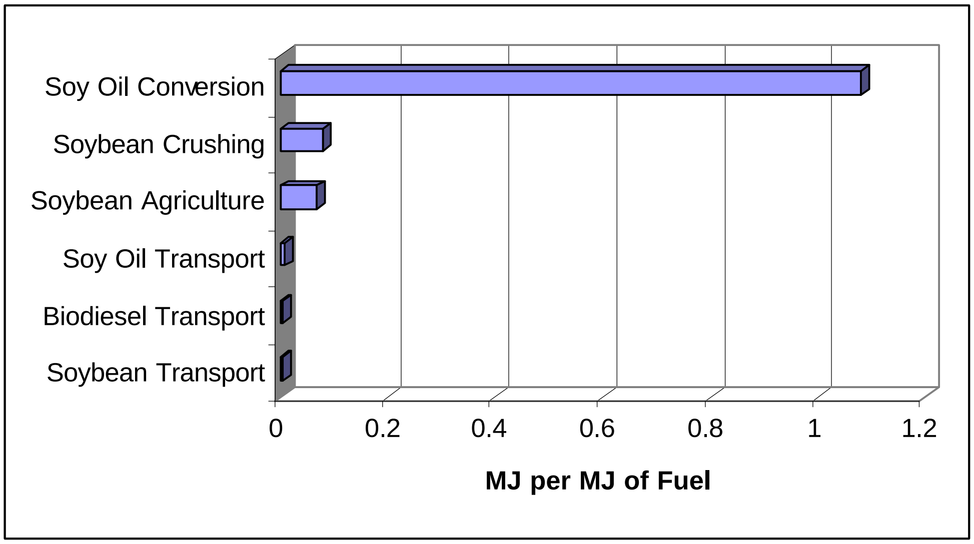


**Figure 4: Ranking of Primary Energy Demand for Stages of the Biodiesel Life Cycle**

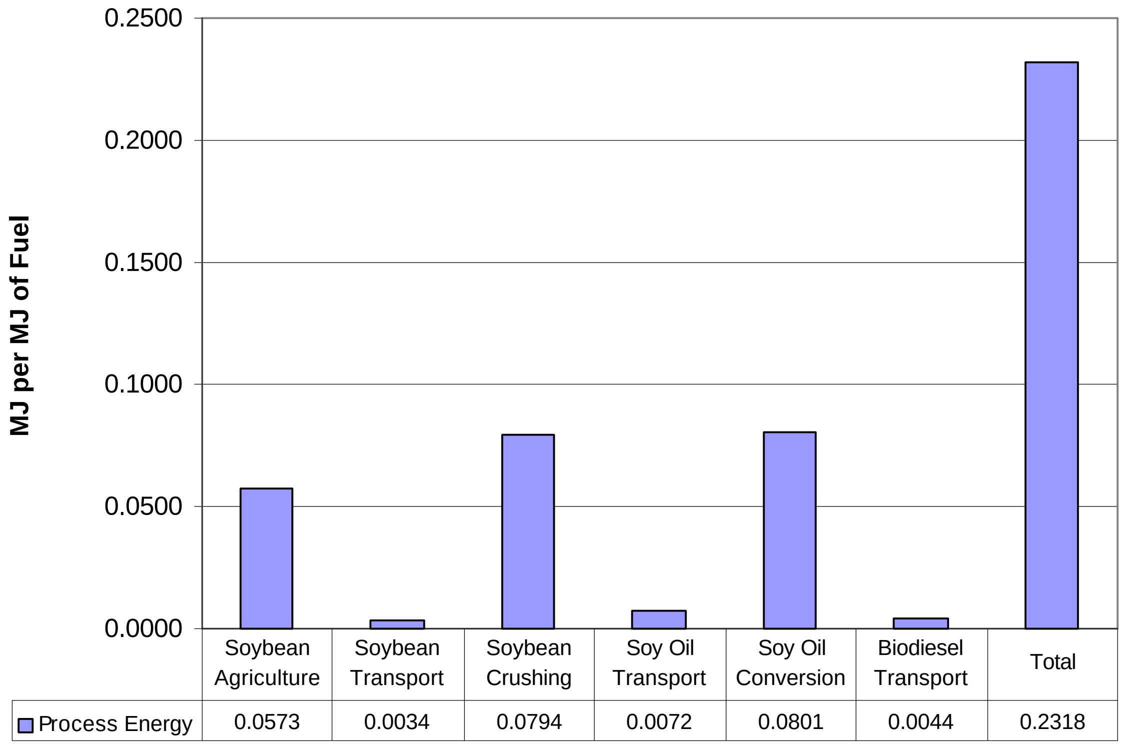


**Figure 5: Process Energy Requirements for Biodiesel Life Cycle**

**Table 6: Fossil Energy Requirements for the Biodiesel Life Cycle**

| Stage | Fossil Energy (MJ per MJ of Fuel) | Percent |
|---|---|---|
| Soybean Agriculture | 0.0656 | 21.08% |
| Soybean Transport | 0.0034 | 1.09% |
| Soybean Crushing | 0.0796 | 25.61% |
| Soy Oil Transport | 0.0072 | 2.31% |
| Soy Oil Conversion | 0.1508 | 48.49% |
| Biodiesel Transport | 0.0044 | 1.41% |
| Total | 0.3110 | 100.00% |

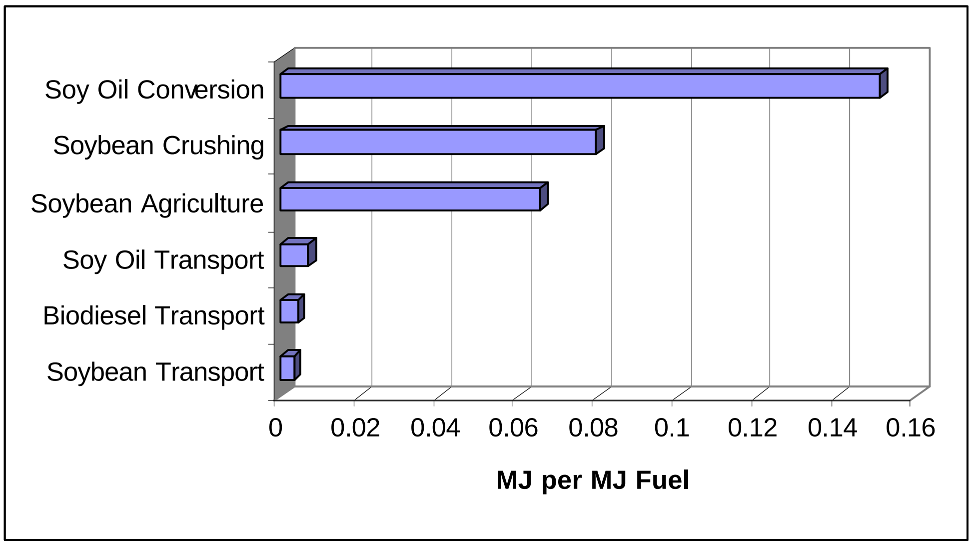


**Figure 6: Fossil Energy Requirements versus Fuel Product Energy for the Biodiesel Life Cycle**

### *2.4.1.1.5 Effect of Biodiesel on Life Cycle Energy Demands*

Compared on the basis of primary energy inputs, biodiesel and petroleum diesel are essentially equivalent. Biodiesel has a life cycle energy efficiency of 80.55%, compared to 83.28% for petroleum diesel. The slightly lower efficiency reflects a slightly higher demand for process energy across the life of cycle for biodiesel. On the basis of fossil energy inputs, biodiesel enhances the effective use of this finite energy resource. Biodiesel leverages fossil energy inputs by more than three to one.

### 2.4.1.2 $CO_2$ Emissions

#### *2.4.1.2.1 Accounting for Biomass-Derived Carbon*

Biomass plays a unique role in the dynamics of carbon flow in our biosphere. Biological cycling of carbon occurs when plants (biomass such as soybean crops) convert atmospheric $CO_2$ to carbon-based compounds through photosynthesis. This carbon is eventually returned to the atmosphere as organisms consume the biological carbon compounds and respire. Biomass derived fuels reduce the net atmospheric carbon in two ways. First, they participate in the relatively rapid biological cycling of carbon to the atmosphere (via engine tailpipe emissions) and from the atmosphere (via photosynthesis). Second, these fuels displace the use of fossil fuels. Combustion of fossil fuels releases carbon that took millions of years to be removed from the atmosphere, while combustion of biomass fuels participates in a process that allows rapid recycle of $CO_2$ to fuel. The net effect of shifting from fossil fuels to biomass-derived fuels is, thus, to reduce the amount of $CO_2$ present in the atmosphere.

Because of the differences in the dynamics of fossil carbon flow and biomass carbon flow to and from the atmosphere, biomass carbon must be accounted for separately from fossil-derived carbon. The LCI model tracks carbon from the point at which it is taken up as biomass via photosynthesis to its final combustion as biodiesel used in an urban bus. The biomass-derived carbon that ends up as $CO_2$ leaving the tailpipe of the bus is subtracted from the total $CO_2$ emitted by the bus because it is ultimately reused in the production of new soybean oil. In order to ensure that we accurately credit the biodiesel LCI for the amount of recycled $CO_2$, we provide a material balance on biomass carbon.

The material balance shows all the biomass carbon flows associated with the delivery of 1 bhp-h of engine work (Figure 7). For illustration purposes, only the case of 100% biodiesel is shown. Lower blend rates proportionately lower the amount of biomass carbon credited as part of the recycled $CO_2$. Carbon incorporated in the meal fraction of the soybeans is not included in the carbon balance. Only carbon in the fatty acids and triglycerides that are used in biodiesel production are tracked. Not all the carbon incorporated in fatty acids and triglycerides ends up as $CO_2$ after combustion of biodiesel. Some oil loss occurs in the meal by-product. Glycerol is removed from the triglycerides as a by-product. Fatty acids are removed as soaps and waste. Finally, carbon released in combustion ends up in the form of $CO_{2,}$ CO, THC, and TPM. Of the 169.34 grams of carbon absorbed in the soybean agriculture stage, only 148.39 grams (87%) end up in biodiesel. After accounting for carbon that ends up in other combustion products, 148.05 grams of carbon end up as 543.34 grams of tailpipe $CO_2$. This $CO_2$ is subtracted from the diesel engine emissions as part of the biological recycle of carbon. No credit is taken for the 13% of the carbon that ends up in various by-products and waste streams.

#### *2.4.1.2.2 Comparison of $CO_2$ Emissions for Biodiesel and Petroleum Diesel*

Table 7 summarizes $CO_2$ flows from the total life cycles of biodiesel and petroleum diesel and the total $CO_2$ released at the tailpipe for each fuel. The dominant sources of $CO_2$ for both the petroleum diesel life cycle and the biodiesel life cycle is the combustion of fuel in the bus. For petroleum diesel, $CO_2$ emitted from the tailpipe of the bus represents 86.54% of the total $CO_2$ emitted across the entire life cycle of the fuel. Most remaining $CO_2$ comes from emissions at the oil refinery, which contributes 9.6% of the total $CO_2$ emissions. For biodiesel, 84.43% of the $CO_2$ emissions occur at the tailpipe. The remaining $CO_2$ comes almost equally from soybean agriculture, soybean crushing, and conversion of soy oil to biodiesel.

At the tailpipe, biodiesel emits 4.7% more $CO_2$ than petroleum diesel, most of which is renewable. The nonrenewable portion comes from the methanol. Biodiesel generates 573.96 g/bhp-h compared with 548.02 g/bhp-h for petroleum diesel. The higher $CO_2$ levels result from more complete combustion and the concomitant reductions in other carbon-containing tailpipe emissions. As Figure 8 shows, the overall life cycle emissions of $CO_2$ from B100 are 78.45% lower than those of petroleum diesel. The reduction is a direct result of carbon recycling in soybean plants. B20, the most commonly used form of biodiesel in the US, reduces net $CO_2$ emissions by 15.66% per gallon of fuel used.

**Table 7: Tailpipe Contribution to Total Life Cycle $CO_2$ for Petroleum Diesel and Biodiesel (g $CO_2$/bhp-h)**

| Fuel | Total Life Cycle Fossil $CO_2$ | Total Life Cycle Biomass $CO_2$ | Total Life Cycle $CO_2$ | Tailpipe Fossil $CO_2$ | Tailpipe Biomass $CO_2$ | Total Tailpipe $CO_2$ | % of Total $CO_2$ from Tailpipe |
|---|---|---|---|---|---|---|---|
| Petroleum Diesel | 633.28 | 0.00 | 633.28 | 548.02 | 0.00 | 548.02 | 86.54% |
| B100 | 136.45 | 543.34 | 679.78 | 30.62 | 543.34 | 573.96 | 84.43% |

### *2.4.1.3 Primary Resource Consumption for Biodiesel and Petroleum Diesel*

The use of B100 as a substitute for petroleum diesel effects a 95% reduction in life cycle consumption of petroleum. Figure 9 compares petroleum oil consumption for petroleum diesel, B20, and B100. The 20% blend of biodiesel provides a proportionate reduction of 19%.

Consumption of coal and natural gas is a different story (Figure 10). The use of B100 increases life cycle consumption of coal by 19%. This reflects the higher overall demand for electricity in the biodiesel life cycle, relative to petroleum diesel. Electricity demand for soybean crushing is the dominant factor in electricity consumption for biodiesel because of the mechanical processing and solids handling equipment involved in this step. Life cycle consumption of natural gas increases by 77% for biodiesel versus petroleum diesel. Two factors contribute to this increase: 1) the assumed use of natural gas for the supply of steam and process heat in soybean crushing and soy oil conversion, and 2) the use of natural gas to produce methanol used in the conversion step.

The biodiesel life cycle imposes a higher burden on water resources than the petroleum diesel life cycle. Water use for petroleum diesel is not even visible on a plot scaled to show biodiesel use (Figure 11). That is because the biodiesel life cycle uses water at a rate that is three orders of magnitude higher than that of petroleum diesel. The impact of this water use is not addressed in this report. We offer no simple way to compare water use between the two life cycles because there is no simple equivalency in its use and final disposition.

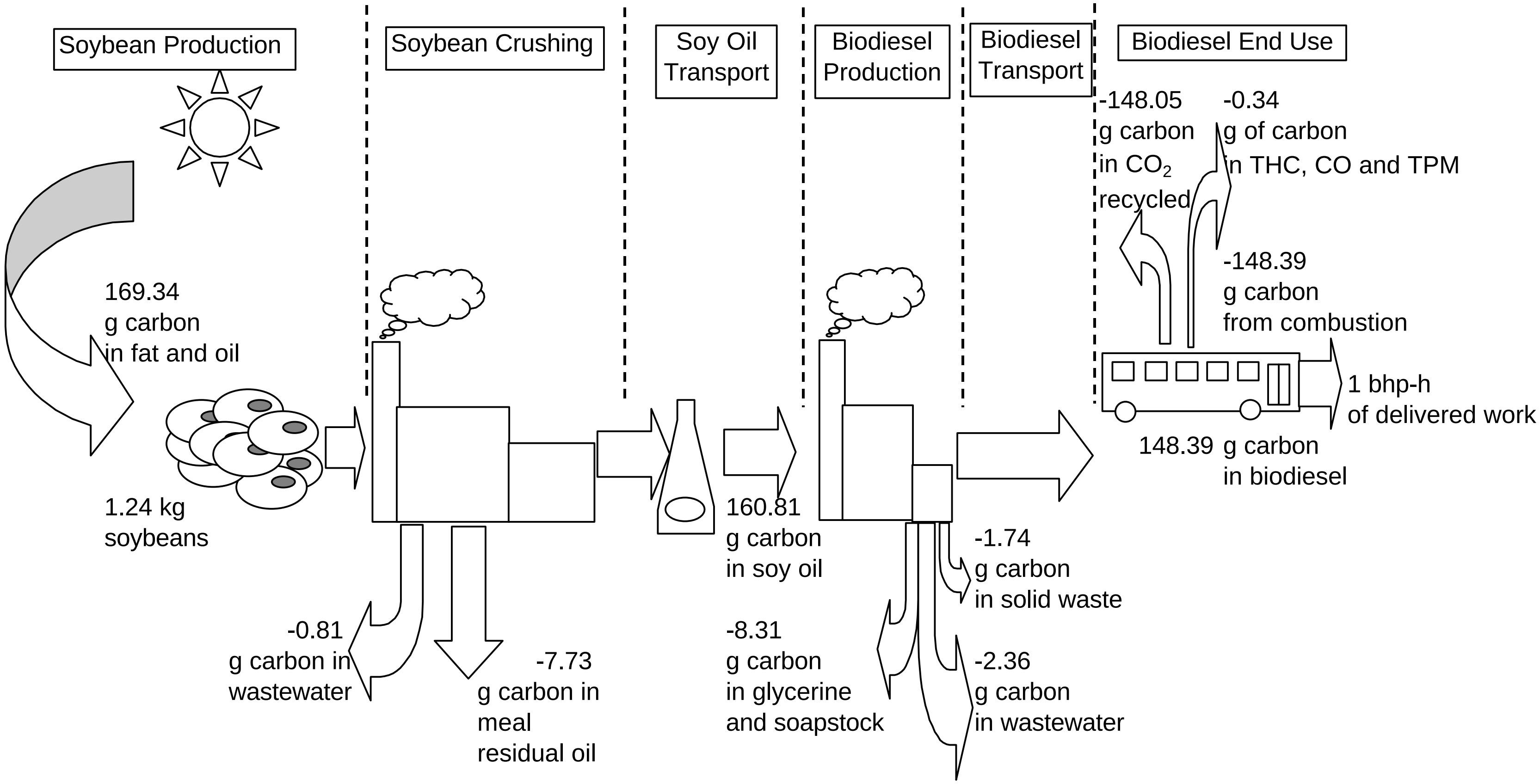


**Figure 7: Biomass Carbon Balance for Biodiesel Life Cycle (g carbon/bhp-h)[12]**

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[12] All numbers presented as carbon equivalent. To calculate actual $CO_2$ emissions, multiply carbon equivalent numbers by 3.67 (the ratio of the molecular weight of $CO_2$ divided by the molecular weight of carbon).

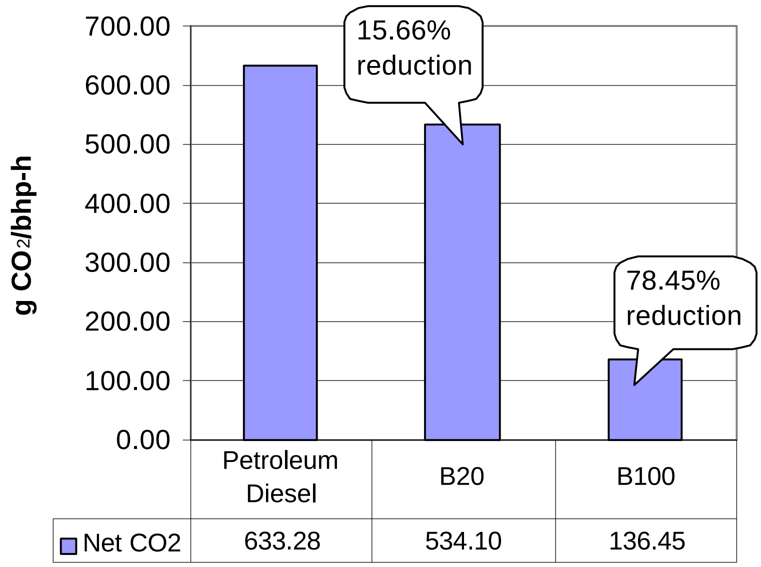



**Figure 8: Comparison of Net $CO_2$ Life Cycle Emissions for Petroleum Diesel and Biodiesel Blends**[13]

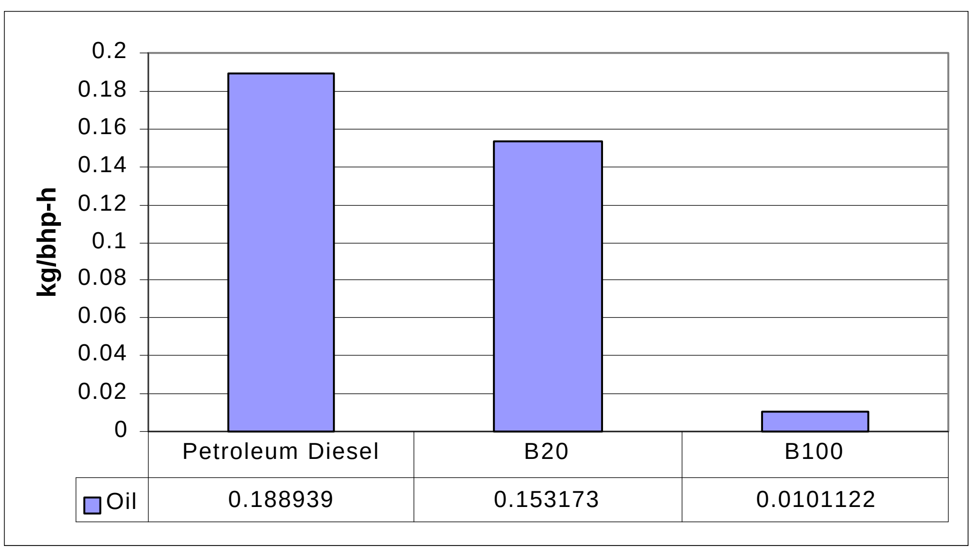



**Figure 9: Petroleum Consumption for Petroleum Diesel, B20, and B100**

[13] Net $CO_2$ calculated by setting biomass $CO_2$ emissions from the tailpipe to zero.

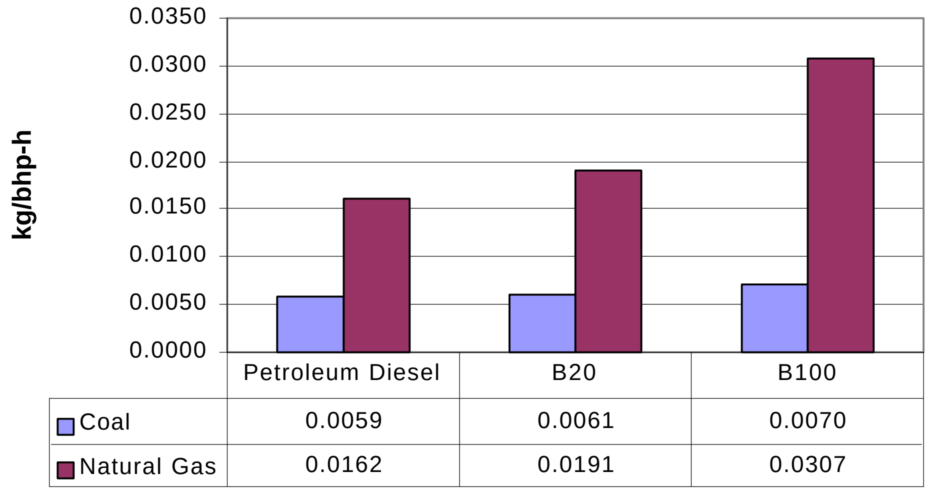



**Figure 10: Coal and Natural Gas Consumption for Petroleum Diesel, B20, and B100**

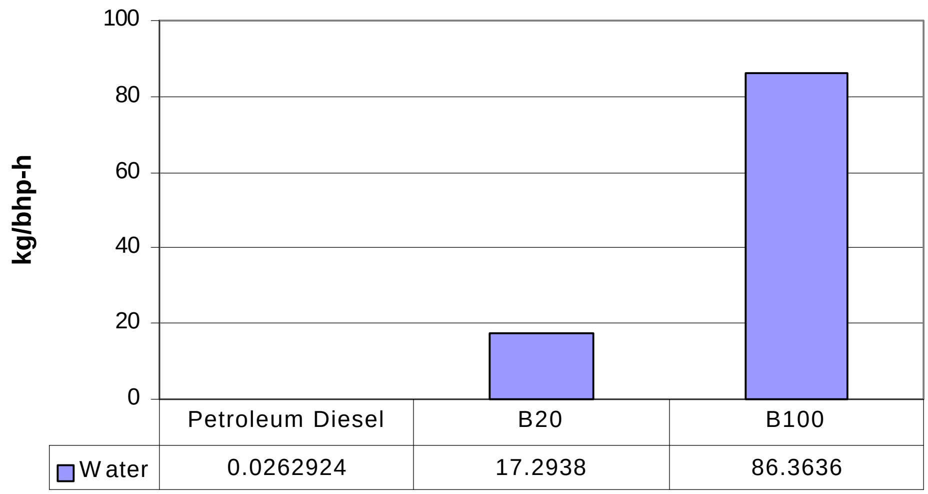



**Figure 11: Water Use for Petroleum Diesel, B20, and B100**

#### *2.4.1.4 Life Cycle Emissions of Regulated and Nonregulated Air Pollutants*

Regulated air pollutants include the following:

- Carbon Monoxide (CO)
- Nitrogen Oxides ($NO_x$)
- Particulate Matter Less Than 10 Microns (PM10)
- Sulfur Oxides ($SO_x$)
- Non Methane Hydrocarbons (NMHC)

The emissions of these air pollutants are regulated at the tailpipe for diesel engines. Sulfur dioxide ($SO_x$) does not have specific tailpipe limits, but it is controlled through sulfur content of the fuel. Other air emissions included in this study are methane ($CH_4$), benzene, formaldehyde, nitrous oxide ($N_2O$), hydrochloric acid (HCl), hydrofluoric acid (HF), and ammonia. $N_2O$ is associated with agricultural field emissions. HCl and HF are associated with coal combustion in electric power stations. Ammonia is released primarily during fertilizer production.

#### *2.4.1.4.1 Comparison of Life Cycle Air Emissions for Biodiesel and Petroleum Diesel*

Figure 12 summarizes the differences in life cycle air emissions for B100 and B20 versus petroleum diesel fuel. In this section, we discuss overall differences in the emissions of the biodiesel and petroleum life cycles. More detail on the sources of the differences is presented in section 9.1.4 Life Cycle Emissions of Regulated and Nonregulated Air Pollutants.

We report particulate matter and hydrocarbons differently from the definitions used by EPA in their regulations. This difference in reporting is due to variations in how different data sources for the stages of the life cycle report these emissions. Benzene and formaldehyde emissions are not consistently reported. Some sources explicitly define emissions for non-methane hydrocarbons (NMHC), while others do not specify this distinction. Hydrocarbon data are reported as THC, defined as:

$$THC = \left(CH_4 + Benzene + formaldehyde + HC_{unspecified} + HC_{noCH4}\right)$$

where:

THC = total hydrocarbons

$CH_4$ = methane

$HC_{unspecified}$ = unspecified hydrocarbons

$HC_{noCH4}$ = hydrocarbons excluding methane

Likewise, particulates are combined as a single category according to the following formula:

$$TPM = \left(PM10 + PM_{unspecified}\right)$$

where:

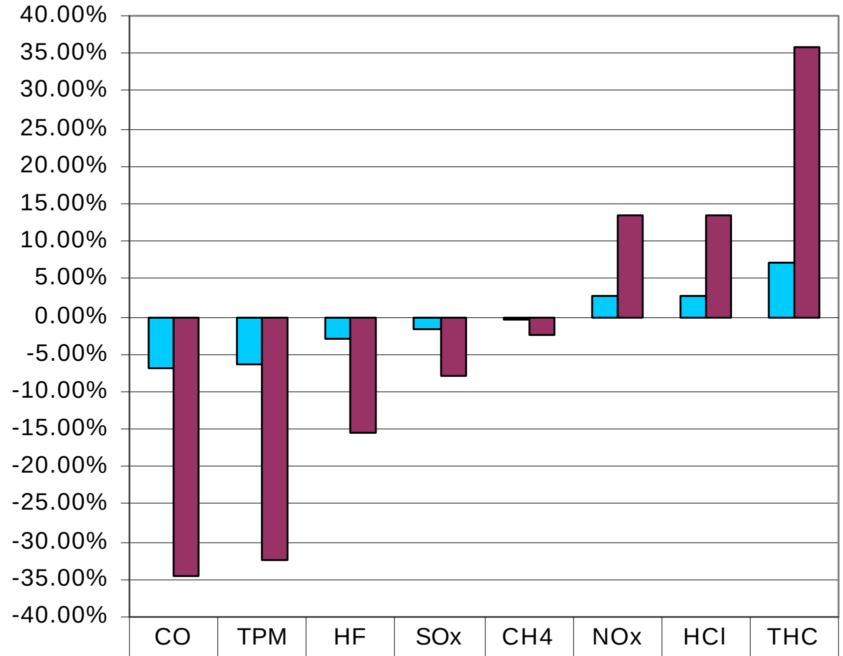
TPM = total particulate matter

PM10 = particulate matter less than 10 micron

$PM_{unspecified}$ = unspecified particulate matter

The replacement of petroleum diesel with biodiesel in an urban bus reduces life cycle air emissions for all but three of the pollutants we tracked. The largest reduction in air emissions that occurs when B100 or B20 are used as a substitute for petroleum diesel is for CO. Reductions in CO reach 34.5% when using B100. The effectiveness of B20 in reducing life cycle emissions of CO drops proportionately with the blend level. Biodiesel could, therefore, be an effective tool for mitigating CO in EPA's designated CO non-attainment areas[14].

[14] These are urban areas in the U.S. identified as not currently meeting National Ambient Air Quality Standards for levels of carbon monoxide.




| | CO | TPM | HF | SOx | CH4 | NOx | HCl | THC |
|---|---|---|---|---|---|---|---|---|
| B20 | -6.90% | -6.48% | -3.10% | -1.61% | -0.51% | 2.67% | 2.71% | 7.19% |
| B100 | -34.50 | -32.41 | -15.51 | -8.03% | -2.57% | 13.35% | 13.54% | 35.96% |

**Figure 12: Life Cycle Air Emissions for B100 and B20 Compared to Petroleum Diesel Life Cycle Air Emissions**

B100 exhibits life cycle emissions of total particulates (TPM) that are 32.41% lower than those of the petroleum diesel life cycle. As with CO, the effectiveness of biodiesel in reducing TPM drops proportionately with blend level. This improvement in TPM emissions is a direct result of reductions in PM10 at the tailpipe of the bus. Tailpipe emissions of PM10 are 68% lower for urban buses operating on B100 versus petroleum diesel. PM10 emitted from mobile sources is a major EPA target because of its role in respiratory disease. Urban areas represent the greatest risk in terms of numbers of people exposed and level of PM10 present. Use of biodiesel in urban buses is potentially a viable option for controlling both life cycle emissions of TPM and tailpipe emissions of PM10[15].

Biodiesel's life cycle produces 35% more THC than petroleum diesel's life cycle. This is in spite of the fact that tailpipe emissions of THC for B100 are 37% lower. The level of emissions of hexane that occur in the soybean crushing stage overshadows the tailpipe benefits[16]. In understanding the implications of the higher life cycle emissions, it is important to remember that emissions of hydrocarbons, as with all of the air pollutants discussed, have localized effects. In other words, it makes a difference *where* these emissions occur. The fact that biodiesel's hydrocarbon emissions at the tailpipe are lower may mean that

[15] Among the options under consideration by EPA are regulations that would control levels of PM2.5, as opposed to PM10. PM2.5 includes particles of 2.5 microns or less in diameter. That is, EPA is focusing its attention on the very smallest particles in ambient air. Data collected in this study focus on PM10. While our results bode well for lowering levels of PM10, no information is available on the effect of biodiesel on this new class of smaller particles.

[16] See section 9.1.4.3 Comparison of Life Cycle Air Emissions from Biodiesel and Petroleum Diesel for more details.